Modelling of impact using adaptive discrete element techniques

M.G. Cottrell[a], D.R.J. Owen[b,*]

[a]Rockfield Software Ltd, Technium, Kings Road, Prince of Wales Dock, Swansea, SA1 8PH, UK
[b]Civil and Computational Centre, University of Wales, Swansea, SA2 8PP, UK

Abstract

For many problems encountered within the defence industry (and many others), numerical modelling has suffered from one principal weakness: for many applications the associated deformed finite element mesh can no longer provide an accurate description of the deformed material, whether due to large ductile deformation, or for the case of brittle materials, degradation into multiple bodies.

Therefore, the primary objective of this paper is to present a methodology demonstrating the potential benefits of explicitly coupling adaptive remeshing methods to the technique of discrete fracture insertion, in order to provide an adaptive discontinuous solution strategy that is computationally robust and efficient. The proposed numerical approach has been incorporated into the finite and discrete element code ELFEN.

Keywords: Adaptivity; Discrete element; Ceramic; Fracture; Impact

---

1. Introduction

The purpose of this study is to demonstrate that techniques based on continuum adaptive remeshing and discrete element fracture can be explicitly coupled to obtain well-defined and quality time-resolved results for the impact of projectiles into ceramics and other quasi-brittle materials. Enhancement of the understanding of the fracture processes, which occur for various impact velocities, is of primary importance.

2. Continuum adaptive remeshing

Adaptive remeshing is today becoming an increasingly recognised important feature of finite element modelling in areas of application such as cold forging, crash worthiness tests and, of principal interest here, dynamic impact tests on quasi-brittle materials. The key factors associated with any adaptive mesh generation analysis are:

- The ability to base models on a geometric entity or assignment level.
- Indication of the quality associated with element distortion for a given mesh.
- The automated prediction of element density within a newly generated mesh.
- The accurate transfer of history-dependent variables between the two meshes.

A large amount of literature associated with these topics can be found elsewhere [1,2], and it is the intention of this paper to provide only a brief description of techniques that can be successfully employed to provide an efficient coupled adaptive/discrete formulation.

Mesh adaptivity is the process by which the element mesh is changed at selected intervals, either to preserve the quality of element shape or to control the error in the solution. Mesh adaptation is triggered by control criteria, which monitor threshold values of specific problem parameters. Typical quantities such as element distortion, or element and nodal quantities such as velocity gradients are often employed. A remeshing indicator based on element distortion is used in this work and has proven to provide an efficient criterion for large deformation problems. In addition, an error estimator is employed to provide an initial prediction of the element density distribution required in the new finite element mesh. The implementation of the adopted approach within the combined finite discrete element code ELFEN can be found within [1,2,3].

The development of error estimator procedures for nonlinear problems is still the subject of intense research and, as yet, no universal measure that is applicable to

---

* Corresponding author. E-mail: d.r.j.owen@swansea.ac.uk

Computational Fluid and Solid Mechanics 2005
K.J. Bathe (Editor)

completely general problems is available. Consequently, explicit error measures are currently employed to control the mesh density for classes of problems exhibiting specific phenomena. For problems in which the strain fields are predominantly elastic and continuous the standard elastic energy norm indicator can be used to good effect.

For problems involving strain localisation, as is the case in multi-fracturing solids, the current incremental strain rate provides a very effective measure for predicting the new mesh density requirements. This methodology is based on defining a heuristic element size based on the distribution of the current total incremental strain rate or inelastic material measures. This is implemented by providing information in a piecewise linearly interpolated manner. The methodology provides a computationally efficient strategy in that a high mesh density is produced in regions with high strain rates, with coarse refinements in areas of low strain rate activity.

In the examples presented in this work the advancing front formulation has been employed for performing the remeshing process. Various strategies to transfer the field variables from the original finite element mesh to the newly generated grid have been implemented (e.g. [1,2,3]), and have proven successful for the solution of nonlinear problems, where the key issue is the minimisation of the diffusion of field variables during the transfer process.

3. Discrete fracture insertion

Traditionally, the finite element method has focused on continuum modelling, however for many applications it is necessary to degrade a single body into a set of independent physical entities. The transition of a brittle body from a continuum description into a discrete (or multi-body) system is developed from the dispersed micro cracks coalescing into macroscopic fractures.

In this work the onset of discrete fracture is directly considered from the anisotropic rotating smeared crack plasticity model [3,4,5]. This model utilises a strain softening formulation to represent the degradation of strength in the tensile regime. The smeared crack model provides a mechanism for directional softening within a continuum framework by envisaging a cracked solid as an equivalent anisotropic continuum with degraded properties in directions normal to crack band orientation. After initial yield the rotating crack formulation introduces anisotropic damage by degrading the elastic modulus in the direction of the current principal stress invariant.

Although energy dissipation in the crack band model is rendered objective by normalising the softening curve with respect to the specific fracture energy, the spatial localisation is necessarily arbitrary. Optional formulations of regularisation techniques, which render the mesh discretisation objective, include non-local damage models, gradient constitutive models, viscous regularisation and fracture energy releasing/strain softening approaches, and a comprehensive overview of the various techniques used to obtain mesh objectivity is given in [4].

Within a numerical simulation environment, the insertion of discrete fractures into a continuum domain introduces additional degrees of freedom that are associated with the nodes introduced to define the fracture geometry. Furthermore, the introduction of discrete fractures also introduces additional contact surfaces, with specified interaction laws, that must be included in the finite element solution procedure. The process of inserting a discrete fracture into a continuum-based finite element mesh follows a set of three key steps. Firstly, the creation of a non-local failure map, which is based upon the weighted nodal averages of the failure parameters within individual elements, is required. Then the failure map is used to determine the onset of local fracture within the domain. Once the onset of fracture has been determined, then the final task is to perform the topological update whereby a discrete fracture is inserted into the domain, and additional nodes and elements are inserted, and the necessary elemental connectivities updated.

4. Numerical simulations

A numerical simulation that demonstrates the coupled adaptive discrete formulation is based upon the experiments presented by Riou [6]. The impacting cylinder is 20 mm in length and 11 mm in diameter, which impacts a silicon carbide with an initial velocity ranging from 100 to 350 ms^{-1}.

The metallic elements including the RHA impactor and the confinement are numerically modelled using the Johnson-Cook viscoplastic constitutive model [7]. The domain is initially discretised with 3-node triangular elements. The use of triangular elements as opposed to the 4-node quadrilateral elements is due to the fracture insertion technology currently available only for the 3-node element. The inelastic strain has been used as a measure for controlling the mesh densities associated with the steel impactor. For the ceramic material mesh density prediction is based on the total incremental strain rate.

An important feature is the evolution of the finite element mesh associated with the adaptive remeshing scheme. The driving motivation behind the proposed technology is the ability to realise a numerical solution with a high level of accuracy with efficient computational costs. The means of controlling the finite element mesh size using a criterion based upon the total incremental strain rate term appears to function well for the fragmenting silicon carbide. In addition, when this is combined with fracture evolution criterion [1] it provides the modeller with a flexible strategy for the efficient representation of both ductile and quasi-brittle systems using coupled adaptive remeshing and discrete fracture insertion processes.

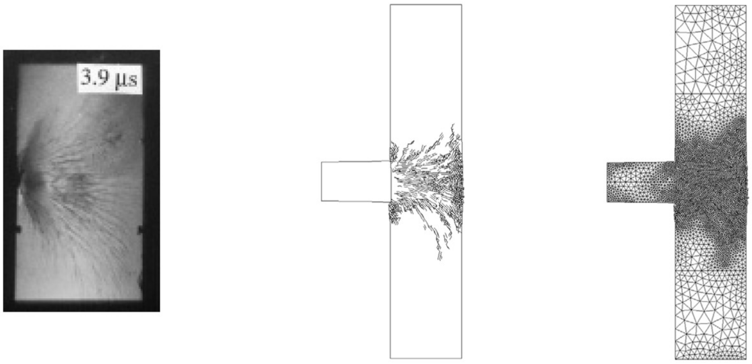
Figure 1 presents the simulated fracture patterns attained for the case of the silicon carbide target impacted at 203 ms^{-1} using the proposed methodology. It is evident that the technology is capable of capturing all of the salient features present within the experimental tests. The numerical simulations correctly identify keys features, such as conical type fractures dominating the fragmentation process. In addition, a degree of spalling type failure is also accurately predicted on the distal face of the ceramic beam as well as the impact interface.

A second numerical example considers the experiments performed by Field [8], in which spherical pellets of varying materials, including steel, tungsten carbide and lead, were impacted at low velocity into ceramic and glass target plates. In a similar fashion to the previous simulation, the initial discretisation consists of a uniform distribution of 3-node linear triangular elements.

The initial mesh density for the simulation is prescribed as 0.75 mm, however through the adaptive remeshing and discrete fracture algorithms, elements ranging from a minimum 0.10 mm to a maximum 1.50 mm will be introduced into the domain.

The total incremental strain rate measure has again been used for controlling the mesh densities associated with both the sintox alumina target and the hardened steel pellet. The use of the total incremental strain rate measure as a means for controlling the predicted mesh densities is preferred over the inelastic strain measure, for the case of a discrete description, since inelastic straining is typically minimal during the fracture process of quasi-brittle materials. Figure 2 presents the simulated fracture patterns attained using the proposed methodology of explicitly coupling continuum adaptive remeshing with discrete fracture insertion processes [2,3,4,5]. Upon comparison with [8], it is clear that the technology is capable of capturing all of the prominent features present within the experimental findings.

(a) 3.9 microseconds



(b) 7.9 microseconds

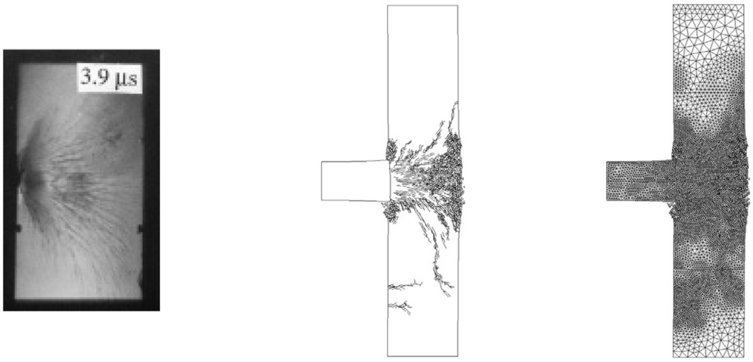
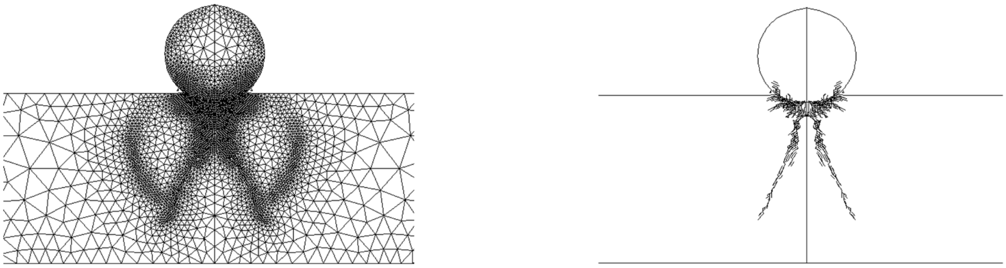
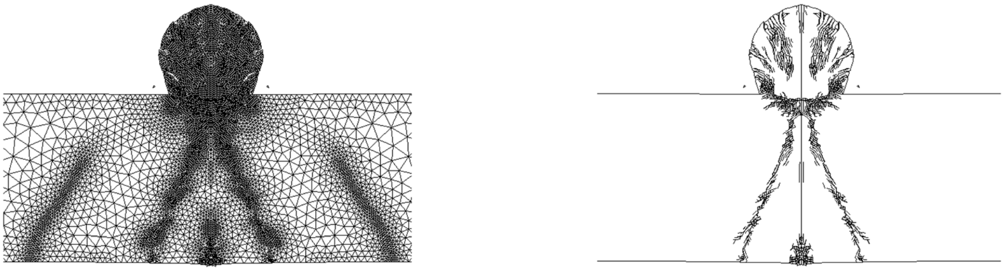


Fig. 1. Experimental fracture distribution, and simulated discrete fracture and mesh development, for times post impact of (a) 3.90 microseconds and (b) 7.90 microseconds.



(a) 2.00 microseconds



(b) 4.00 microseconds

Fig. 2. Finite element mesh evolution and simulated discrete fracture development in an unconfined 8 mm thick Sintox alumina target impacted at 300 ms^{-1}, with times post impact of (a) 2.00 microseconds, and (b) 4.00 microseconds.

5. Conclusions

In this paper, it has been shown that the use of adaptive remeshing and discrete element techniques can be effectively coupled and employed in the complex numerical modelling of ceramic armoured systems when subjected to normal low velocity metallic impacts. Specifically it has been shown, for situations that involve strain localisation phenomena, such as multi-fracturing quasi-brittle solids, strain rate criteria can be used to develop appropriate adaptive mesh predictions. An important issue that arises from the present work is the ability to correctly couple the finite element mesh size with the fracture insertion process.

Currently the length of the fracture is dictated by the size of the adjoining finite elements. However, it is more preferable to be able to define the finite element mesh size from the size of fracture that should be inserted into the system, based on energy release criteria. Local mesh refinement is useful for resolving crack tip fields, and will undoubtedly aid the prevention of premature crack arrest. Furthermore, increased mesh density at the crack tip enables the number of possible crack orientations to increase.

Therefore, it is essential that computational strategies be developed, which can be used to determine the size and location of a flaw completely independently of the surrounding finite element mesh. It is also worthy of note that remeshing is a means of departing from directional bias associated with a fixed finite element mesh employed in the case of inter-element fracturing [5].

The strategy presented herein has been initially developed in the context of a 2D framework. However this numerical approach has been recently extended to provide a modelling capability for complex 3D systems containing advanced quasi-brittle fracturing materials together with rapidly expanding explosive products. The modelling of such inherently different material types clearly requires an approach such as the present coupled adaptive discrete element technique.

References

[1] Cottrell MG. The development of rational computational strategies for modelling high velocity impact. PhD thesis, University of Wales, Swansea, 2002.

[2] Cottrell MG, Yu J, Wei Z, Owen DRJ. The numerical modelling of ceramics subject to impact using adaptive discrete techniques. Eng Computations: Int J Comput Aided Design 2003;20:82–106.

[3] Yu J. A contact interaction framework for numerical simulation of multi-body problems and aspects of damage and fracture for brittle materials. PhD Thesis, University of Wales, Swansea, 1999.

[4] Klerck PA. The finite element modelling of discrete fracture in quasi-brittle materials. PhD Thesis, University of Wales, Swansea, 2000.

[5] Owen DRJ, Feng YT, de Souza Neto EA, Cottrell MG, Wang F, Andrade Pires FM, Yu J. The modelling of multi-fracturing solids and particulate media. Int J Num Methods Eng 2004;60:317–339.

[6] Riou P, Denoul C, Cottenot CE. Visualisation of the damage evolution in impacted silicon carbide ceramics. Int J Impact Eng 1998;21(4):225–235.

[7] Johnson GR, Cook WH. A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures. In: Proc of the 7th Int Symposium on Ballistics, The Hague, The Netherlands, 1983.

[8] Field JE. Investigation of the Impact Response of Various Glass and Ceramic Systems. USARDSG–UK, ARO–E, DAJA45–85–C–0021, University of Cambridge, 1988.